# MARS POLAR LANDER OPERATIONS: NAVIGATION ADVISORY GROUP ACTIVITIES

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**ABSTRACT** - After the loss of the Mars Climate Orbiter (MCO), a team of senior navigation analysts was added to the Mars Polar Lander (MPL) project to help ensure a successful delivery to atmospheric entry. This team, referred to as the Navigation Advisory Group (NAG), performed an independent review of the MPL navigation plan and orbit determination status. Based on their findings, the NAG performed three major tasks: (1) re-evaluated the data types and dynamic models used to determine navigation strategies, (2) monitored thruster activity and refined dynamic model inputs, and (3) introduced an interferometric data type to improve orbit knowledge before the design of the final maneuvers. After the end of the mission, the NAG put forth recommendations for the navigation of future missions.

## 1 - INTRODUCTION

Mars Polar Lander (MPL), with the two Deep Space 2 (DS2) probes, was launched on 3 January 1999 for arrival at Mars on 3 December 1999. All three were mounted to a shared cruise stage for the trip to Mars, and were targeted to approximately 76° South, 195° West. Five trajectory correction maneuvers (TCMs) were used to deliver the spacecraft to their targets. Figure 1 shows the interplanetary cruise trajectory and TCMs 1-4 along with their execution dates.[1]

After the loss of Mars Climate Orbiter (MCO) in September 1999, additional navigation expertise was added to the project to assist with verification and validation of MPL orbit determination and maneuver operations, and to help ensure a successful delivery to atmospheric entry. This team of senior navigation analysts was referred to as the Navigation Advisory Group, or NAG. The NAG performed parallel analyses with minimum interference to the planned MPL navigation team activities. Interaction between the MPL navigation team and NAG members was coordinated through meetings (scheduled once-per-day and before critical events) throughout the remainder of MPL cruise.

### 1.1 - NAG Activities

The NAG reviewed the MPL navigation plan, as well as the status of the orbit determination task. It became clear that it would not be possible to meet the navigation performance described in the plan for three reasons:

[1] TCM-5, which was executed 6.5 h prior to Mars arrival, is not shown due to its close proximity to Mars in the figure.

(i) Stray light from the spacecraft interfered with its ability to use the on-board camera to perform gyro and attitude updates without slewing the spacecraft away from its normal cruise attitude. This would increase the number of thruster events encountered by the spacecraft throughout cruise, adversely affecting the navigation accuracy.

(ii) The ability to model the effects of thruster events based on telemetry received from the spacecraft was not as good as previously assumed. This would increase the magnitude of the TCMs (and their execution uncertainty) over what was planned.

(iii) The enhanced performance expected from the addition of Near Simultaneous Tracking (NST), especially for detection and characterization of acceleration mis-modeling, was not verified. Also, there were very few analysts trained in the processing of this new data type or familiar with its characteristics.

As a result, the NAG calculated a new set of entry statistics that showed a larger error ellipse at Mars entry than had been previously planned. Second, the NAG took the lead working with spacecraft engineers at Lockheed Martin Astronautics (LMA) to improve the modeling of the thruster activity throughout cruise. Finally, to offset the increase in trajectory uncertainty and uncertainty in the quality of the NST measurements, a set of interferometric measurements were made of MPL with respect to a Mars orbiter. These activities helped guarantee the safe delivery of MPL and DS2 to the atmospheric entry aim point.

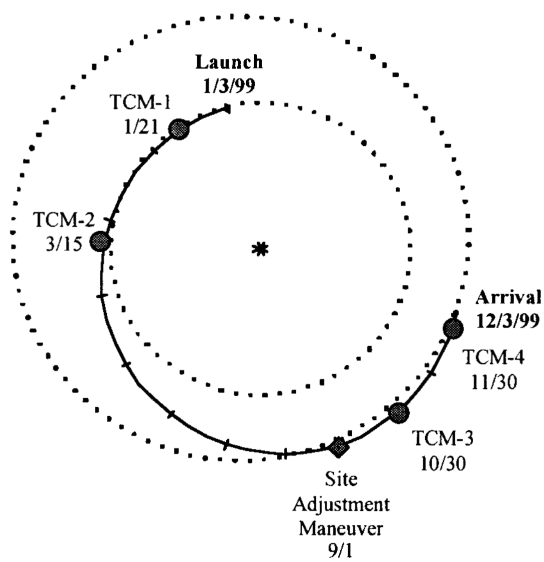


**Fig. 1:** Mars Polar Lander (MPL) Interplanetary Cruise

This paper addresses the analyses and development activities led by NAG members[2]. NAG activities that were collaborations with the MPL navigation team (such as the mapping of the trajectory from the atmospheric entry point to the landing site) are described in [JSRB 00].

## 2 - NAG ANALYSES AND ASSESSMENTS

By October 1999, the NAG had to quickly perform certain analyses and tradeoff studies in order to decide whether any major changes needed to be made to the MPL navigation plan. These analyses covered (1) modeling of spacecraft dynamics, (2) NST as a data type, (3) the potential benefits from

[2] For more information about the MPL mission and approach navigation, please refer to [PDB 00].

the introduction of an interferometric data type, and (4) unification of the results from these studies in a new set of entry statistics.

## 2.1 - Modeling of Spacecraft Dynamics

Three sets of tasks were started which addressed the modeling of spacecraft dynamics. Over time, the net $\Delta V$ imparted to the spacecraft by thruster activity was at least as large, if not larger, than the contribution from solar radiation pressure; therefore, these tasks were given a high priority. First, given the increase in thruster activity due to the unanticipated Star Camera (SCAM) slew events, the inputs that modeled the changes in attitude required validation. Not only did this affect past thruster events, it also required a validation of predicted (future) SCAM slew events. It was important to improve the attitude accuracy so enhancements to the solar radiation pressure model could be made. Second, the process for creating predicted attitude control thrust forces accounting for non-line of sight components required revision as well. Third, pre-fit and post-fit uncertainties were calculated for estimates of dynamic stochastic accelerations, using a set of long arc and short arc solutions.

## 2.2 - Near Simultaneous Tracking (NST)

In the original MPL plan, during the final 30 days of interplanetary cruise, MPL ranging data was to be combined with ranging data from either MCO or the Mars Global Surveyor (MGS). By combining the data and estimating the trajectories of both spacecraft simultaneously, common-mode errors (such as tracking station locations, Earth orientation, troposphere and ionosphere delays, and Mars ephemeredes) were to have canceled out to a large degree. This technique of combining tracking data from two spacecraft was referred to as Near Simultaneous Tracking (NST). The result should have been a more accurate estimate of the MPL trajectory with respect to Mars than could have been obtained with filtering of MPL tracking data only [PHK 98].

In practice, however, this technique had not yet reached operational maturity. The NST procedure used at the stations was to track one spacecraft, then the other within about 15 minutes. The procedure was optimized to keep this inter-track period as short as possible. In doing so, dual sets of receiver channel processors (RCPs) were used, introducing an unmodeled bias into the measurement. As a result, the procedure had to be modified so as to require only one RCP; this modification was not put into place until the end of October, after all the practice NST opportunities.

The range measurement error budget was not totally understood, especially (1) the error growth as a function of time between tracks of the two spacecraft, and (2) the ranging calibration error due to the different radio frequencies used by MPL and MGS. Although some progress was made in refining the range error budget, when orbit solutions with and without NST data were compared, the results of adding NST always appeared to be inconclusive. In addition, there were very few analysts trained in the use of NST data, and little time was available to validate or streamline the procedure. As a result, NST was carried along in some solutions, but it was not used to identify modeling problems in the spacecraft-Mars direction as was originally hoped.

## 2.3 - Interferometric Data

Given the tight entry corridor requirements, the uncertainty in the thruster activity, and the uncertainty of NST, the NAG recommended that a new target-relative measurement be used to verify the Doppler/Range orbit solutions. Interferometric measurements were proposed, using signals from

MPL and the Mars Global Surveyor (MGS) at Mars.[3] The observables, involving two spacecraft and two stations, were given the name "Doubly Differenced Range" (DDR). Tests were begun to verify the usefulness of the MGS signals and the DSN hardware to record the wideband signals. A plan was laid out for a short data acquisition campaign. Possible error sources and failure modes were identified; a schedule and required resources were defined.

## 2.4 - Covariance Analysis

With the new understanding of the spacecraft dynamics and changes in data types, a new set of Mars encounter covariance computations were performed (see Table 1). Three families of solutions were considered: 2-way Doppler and range (this was treated as the baseline), Doppler/Range and NST, and Doppler/range and DDR.

| Cases | | | | | Data Cutoff: TCM-4 (Entry - 5 d) | | Data Cutoff: TCM-5 (Entry - 12 h) | |
|---|---|---|---|---|---|---|---|---|
| Primary Data Types | Mars Ephemeris | Dynamic Stochastics[4] | Differenced Doppler[5]? | Range Bias[6] | **Entry Angle (°)** | **B•R[7] (km)** | **Entry Angle (°)** | **B•R (km)** |
| **Doppler/ Range** | Considered | 10 % | | | 0.43 | 8.5 | 0.31 | 6.2 |
| | | 10 % | ✓ | | 0.36 | 7.1 | 0.3 | 5.9 |
| | | 20 % | ✓ | | 0.38 | 7.5 | 0.31 | 6.2 |
| | | 10 % | ✓ | | 0.48 | 9.5 | 0.35 | 6.9 |
| | | 20 % | ✓ | | 0.5 | 9.8 | 0.37 | 7.3 |
| **Doppler/ Range/ NST** | Estimated | | | | 0.28 | 5.5 | 0.25 | 4.9 |
| | | | | 25 cm | 0.31 | 6.1 | 0.26 | 5.1 |
| | | 10 % | ✓ | 25 cm | 0.27 | 5.4 | 0.25 | 4.9 |
| | | 20 % | ✓ | 25 cm | 0.28 | 5.6 | 0.26 | 5.2 |
| | | 10 % | ✓ | 25 cm | 0.38 | 7.4 | 0.29 | 5.8 |
| | | 20 % | ✓ | 25 cm | 0.39 | 7.7 | 0.31 | 6.2 |
| | | | | 50 cm | 0.36 | 7.1 | 0.27 | 5.3 |
| **Doppler/ Range/DDR** | Estimated | 0.5 ns System Bias | | | 0.35 | 6.8 | 0.29 | 5.7 |

**Table 1:** Mars Polar Lander Orbit Determination Covariance Analysis (1-$\sigma$ Values)

[3] There was no camera system available on-board, so optical navigation measurements were not possible.

[4] *A priori* uncertainty of dynamic stochastics at X% of the root-sum-square of the $\Delta V$s computed by the on-board attitude control system.

[5] The spacecraft plane-of-sky velocity can be measured by collecting station differenced Doppler observables; these are referred to as Differenced Doppler observables.

[6] *A priori* uncertainty in stochastic range biases; each tracking pass was assigned a range bias.

[7] For guidance error calculations at the target body, it is convenient to refer to the two-dimensional dispersion ellipse in the asymptotic approach plane at the target; this plane is commonly referred to as the B-plane. Due to the approach geometry, the error in the direction of increasing latitude (B•R) was a useful metric for comparing different orbit determination data strategies.

## 3 - THRUSTER ACTIVITY

Correctly modeling the MPL thruster activity was clearly vital to delivering the spacecraft to the desired target. Doppler data collected during cruise indicated that the nominal model did not provide adequate predictions, leading to an effort by the NAG to improve the model. Using data from numerous sources, the thruster models were revised several times, resulting in a final model that had roughly twice the $\Delta V$ magnitude as the original model. More importantly, the final model, which was still far from perfect, allowed a sufficiently accurate MPL delivery.

### 3.1 - Thruster Activity Overview

The interface to the navigation team with the record of on-board thruster activity was referred to as the Small Forces File (SFF). The use of the SFF as an integral part of navigation operations was pioneered by MPL.[8] The MPL flight software nominally generated a small forces packet for every thruster firing, which was subsequently telemetered to the ground, as well as being retained on-board as long as possible in case replays were necessary. Once on the ground, small forces packets were converted into SFFs, a text format with one line per packet. For single-thruster pair firings, with spacecraft thruster configuration knowledge, the SFF provides enough information about spacecraft attitude and thruster combination to reconstruct the $\Delta V$ imparted to the spacecraft.

Four thrusters (referred to as RCS thrusters) were used for all MPL attitude control activity during cruise, firing in six different combinations of two thrusters to provide torque about each spacecraft axis (see Figure 2). Each thruster pair imparted net accelerations to the spacecraft. The attitude control thrusters fired predominantly 15 ms pulses, with the rest (only about 5 % of the total) being 30 ms in duration.

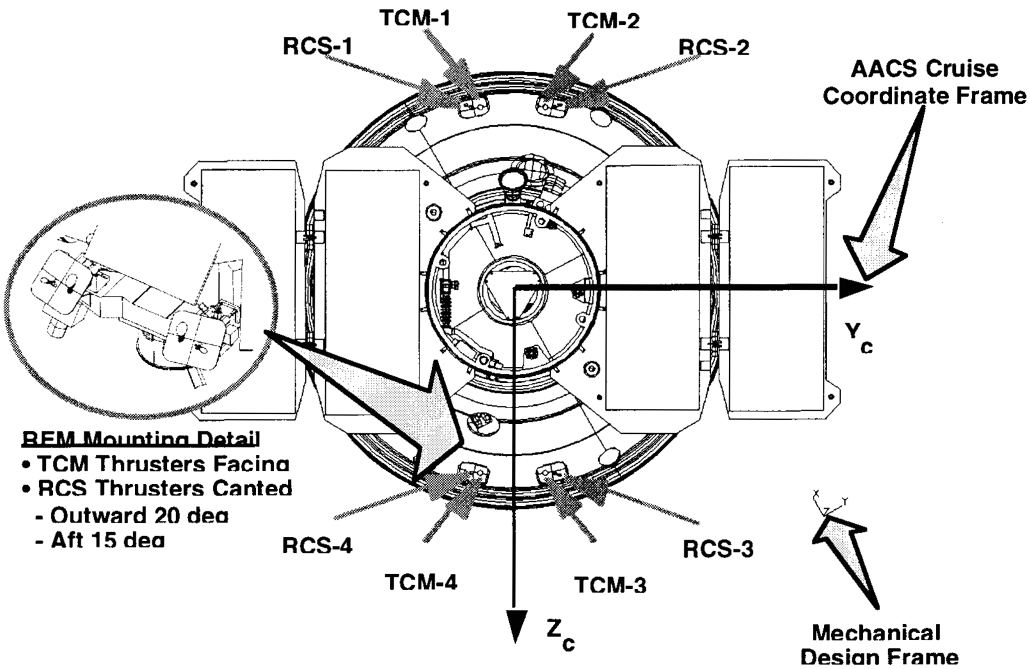


**Fig. 2**: Mars Polar Lander Thruster Geometry

The nominal spacecraft attitude (hereafter referred to as the "com" attitude) pointed the medium gain antenna at the Earth. During the SCAM processing periods, the spacecraft performed two rotations

[8] The SFF is being used for the Stardust mission (which launched less than two months after MPL); its use is being planned for other missions as well.

of about 20-25 degrees to shade the star scanner behind a solar array. The transition between these two attitudes was accomplished by means of a "dead-band walk." The start of such an event was always very distinct, with several pulses being fired immediately to build up to the maximum permitted attitude rates, but at the end the transition was less obvious, as the dead-band limits more gradually halted the turn and normal dead-band activity resumed. Seventy-five minutes was allotted for each dead-band walk, but their average duration was under an hour. Despite their short duration, the amount of thruster activity during a pair of dead-band walks was almost as much as during 24 hours of normal dead-banding, so the dead-band walk modeling contributed significantly to the overall small forces model. These star scanner-related attitude changes had not been planned from pre-launch; no method for accurate modeling of frequent attitude changes had been developed on MPL before this time.

### 3.2 - Analysis of SFF Quality

The first realization of MPL SFF mis-modeling came at the end of October, due in part to the increased tracking coverage that started towards the beginning of that month. In addition, the attitude profile before early October was nominally in the SCAM attitude, with turns surrounding each tracking pass, whereas during most of October the SCAM period was restricted to 4 hours daily at about the same time of day, with multiple passes at the com attitude. The more regular scheduling and increased tracking coverage changes made the effects of small forces errors easier to see in the tracking data. The Doppler pre-fit residuals revealed a pattern of line-of-sight (LOS) Doppler jumps at each deadband walk event, as well as a general LOS acceleration error in between. The evidence for this mis-modeling was also seen in the severe disagreement between orbit determination solutions based on different data type combinations and data arc lengths, which had been noted throughout the mission up to that time. When the nominal SFF was used, the signature in the pre-fit residuals was reduced, but a significant component remained. To completely remove the signature, a scaling factor of 1.75 in combination with a LOS acceleration of $7.2 \times (10^{-12})$ km/s$^2$ was required. The acceleration was thought to be due to a remaining solar pressure error, although it was large compared to the total solar pressure acceleration of roughly $2.5 \times (10^{-11})$ km/s$^2$.

The scale factor and acceleration bias estimates were obtained by evaluating pre-fit Doppler residuals for different candidate values. Even though this approach does not yield the most optimum estimates, it avoided dealing with the complexities of the MPL orbit determination filter setup and associated aliasing concerns, while still producing an acceptable solution for the few variables involved. Consequently, this approach was used for all small forces tuning during model development, with full solution-based approaches being used later to evaluate the results.

### 3.3 - SFF Revisions

With mis-modeling evident in the SFF, the NAG pursued four lines of investigation to address the problem: (1) full orbit determination solutions were run in ways that evaluated the consistency of the dynamic modeling, (2) changes were made to obtain Doppler data through deadband walks, (3) thruster characteristics as they related to MPL were investigated, and (4) available engineering data for possible corrections to the computed $\Delta$Vs were analyzed. All of these activities resulted in useful information that was incorporated in some way into small forces model improvements.

The first evaluation of the simple 1.75 scaling was run using a filter setup that mapped successive data cutoffs to the final B-plane. The same SFF was used for all solutions, so that all data spans used historical rather than predicted small forces inputs. The scaled SFF showed much better consistency than the nominal file, which had frequent multi-sigma jumps and trends in the solution history, much like what was seen in the operational orbit determination history.

The first direct tracks of MPL through dead-band walks surrounding a SCAM attitude were accomplished on November 3, 12, and 20. During the last of these tracks, the LMA spacecraft team also arranged to record attitude rate information. While the Doppler data from these test was extensively analyzed, a number of factors, including the small size of the thruster pulses when compared to even the high sensitivity of the X-band Doppler data, the variability of individual pulses, and the combinations of pulses in timespans too short to allow separate visibility, combined to make the analysis only useful for confirming the overall scale factor of 1.75.

Meanwhile, JPL propulsion analysts obtained all the available test data on thrusters similar in design to the MPL thrusters, and then making judgments on other known effects to come up with an impulse prediction and error bounds. The primary effect studied was the contribution of the "dribble-volume," where residual propellant exhausts through the nozzle over a time span of several seconds, producing a significant amount of impulse relative to that obtained in the first second following a short pulse duration.

Finally, in discussions with the NAG, LMA engineers proposed that the source of the observed errors was due to treating all pulses alike, instead of recognizing that a recently-fired thruster would produce more impulse for the same on-time, due to a hotter catalyst bed. The thruster performance curves showed a factor of 2 difference in impulse between infrequent (limit duty cycle, or "cold") and frequent (pulse mode, or "hot") usage profiles. LMA engineers suggested that 60 sec of preceding off time be a dividing point for using the hot or cold curves for predicting thruster impulse. This algorithm was implemented in ground software as "Revision 5" in the sequence of SFF algorithm updates. The "Rev. 5" SFF became a standard point of comparison throughout much of the rest of the mission.

### 3.4 - Revision J Development

While the Rev. 5 SFFs were an improvement over the nominal model, there were still indications that the model could be further improved. The orbit determination solution consistency over time was worse for Rev. 5 than for the simple 1.75 scaling, and the LOS velocity still showed residual signatures in the Doppler data. The relative abruptness of the factor-of-two transition across the 60-second boundary was also troubling, since it clearly did not correctly represent the pulse characteristics for a significant number of pulses (those between perhaps 30 to 59 second of preceding off time).

At this time, LMA analysts found that the torque about one direction was too high by roughly 60 percent. This was based on a close examination of body rate information implicit in successive small forces packets, combined with the nominal thruster pointing and mounting information and the spacecraft moments of inertia. A "magic vector" was computed that corrected the thrust direction to account for the observed torque. In addition to correcting the torque, this change also corrected the observed LOS velocity. Despite the attractiveness of this correction, its use was viewed with much trepidation, since no obviously acceptable physical explanation was proposed to account for it.

After additional numerical experiments, three modifications went into a new revision (referred to as Ref. J). First, the thrust impulse, instead of having merely a factor of 2 difference between "hot" and "cold" values, now made a distinction between 15 ms and 30 ms pulses, and included a term for dribble-volume effects. Second, the thrust vector orientation was rotated from the nominal direction to nearly the "magic vector" direction. Finally, the solar radiation pressure model was updated at the same time. The resulting orbit determination solution history using Rev. J was more consistent than that using Rev. 5. However, the encounter state projection shifted by 10 km to the south without any indication of being more correct; this shift showed the sensitivity of the orbit solution to unobservable modeling changes.

### 3.4 - Revision R Development

Although the Rev. J SFFs were accepted as the nominal within a day or two (and at this point only 1 week from Mars arrival), its continued use showed that there was still room for improvement. Typical solutions resulted in stochastic acceleration estimates that were higher than expected, combined with fairly large solar radiation pressure model estimates. The encounter state projections also showed significant sensitivity to the use of 10 versus 30 percent stochastic acceleration uncertainties, indicating the nominal acceleration model was not ideal.

At this point, the final model refinement that was pursued was to calculate different vector orientations for the main thruster event and the dribble-volume impulse. This modification, known as Revision R, gave the best agreement between Doppler residuals and attitude rate data to date. However, neither propulsion analysts at JPL nor those at the contractors could validate the introduction of a different effective thrust vector for dribble-volume impulses.

## 4 - DDR MEASUREMENTS

Planning, performing, and processing DDR measurements within the final few weeks of MPL cruise was a challenge. For example, the Deep Space Network (DSN) had removed its DOR (Delta Differential One-way Range) data acquisition system, and the DOR tone function in the spacecraft transponder had been disabled prior to launch. But the Full Spectrum Recorder (FSR), borrowed from the Galileo project, was available. With the FSR it was possible to acquire signals from the spacecraft telemetry sidebands in a single digital baseband channel, making DDR measurements possible.

### 4.1 - Measurement Overview

The DDR observables involved signals from two spacecraft to two stations. Differencing between stations eliminated the biases at the spacecraft. Differencing between spacecraft eliminated the biases at the stations. In this case, the signal from MGS was used as the second spacecraft, or calibration source. The information content of a DDR measurement was the angular offset between the two spacecraft. To the extent that MGS had a well-known position relative to Mars, each measurement provided one component of the angular position of MPL relative to Mars. This component was in the direction of the Goldstone-Canberra baseline projected onto the plane-of-sky.

In past missions, quasar recordings have been used to calibrate instrumental effects at the precise center frequencies of the spacecraft signals. At the time of MPL cruise, the FSR did not have a high enough sample rate to record quasar signals, so it was necessary to use a different approach to do the DDR calibrations. Spacecraft signals to be used in the DDR measurements were selected so that they would all lie within one digital baseband channel of the FSR. All digital processing steps were known, so all baseband effects canceled between spacecraft if properly bookkept. Station clock offsets also cancel between spacecraft. This only leaves dispersive instrumental effects at radio frequency or intermediate frequency as DDR error sources. These effects were not too large, since the DSN front ends are broadband compared to the frequency separation between the spacecraft signals.

### 4.2 - Spacecraft Ranging Signals

A broadband signal, spanning several megahertz, was required to make a range measurement. The DSN routinely uses a range code with a 1 MHz clock to measure the line-of-sight two-way range between a station and a spacecraft. This code generates tones at a spacing of 1 MHz on each side of the carrier, so the signal bandwidth is 2 MHz. These signals could also be used for differential one-way ranging, but there were several drawbacks for MPL: (1) an uplink was required for each spacecraft, (2) the two-way downlink carriers were separated by 12 MHz in frequency, (3) the signal spanned bandwidth was only 2 MHz. The first problem is an operational burden, due to the 26-minute round trip light time and slewing of the antennas between spacecraft for data acquisition. The other problems reduced the cancellation of ground station instrumental effects at RF and IF.

The downlink spectra for each spacecraft were studied to select the best signals to use for the DDR measurements. For MGS, the carrier and inner DOR tone, at a spacing of 3.825 MHz above the carrier, were selected. For MPL, the plus and minus first and seventh harmonics of the 360 kHz telemetry sub-carrier were selected. Figure 3 shows the spectra of the signals used for DDS data acquisition. MGS was observed in the one-way mode, while MPL was observed in the two-way coherent mode[9]. A third DSN station was used for the MPL uplink.

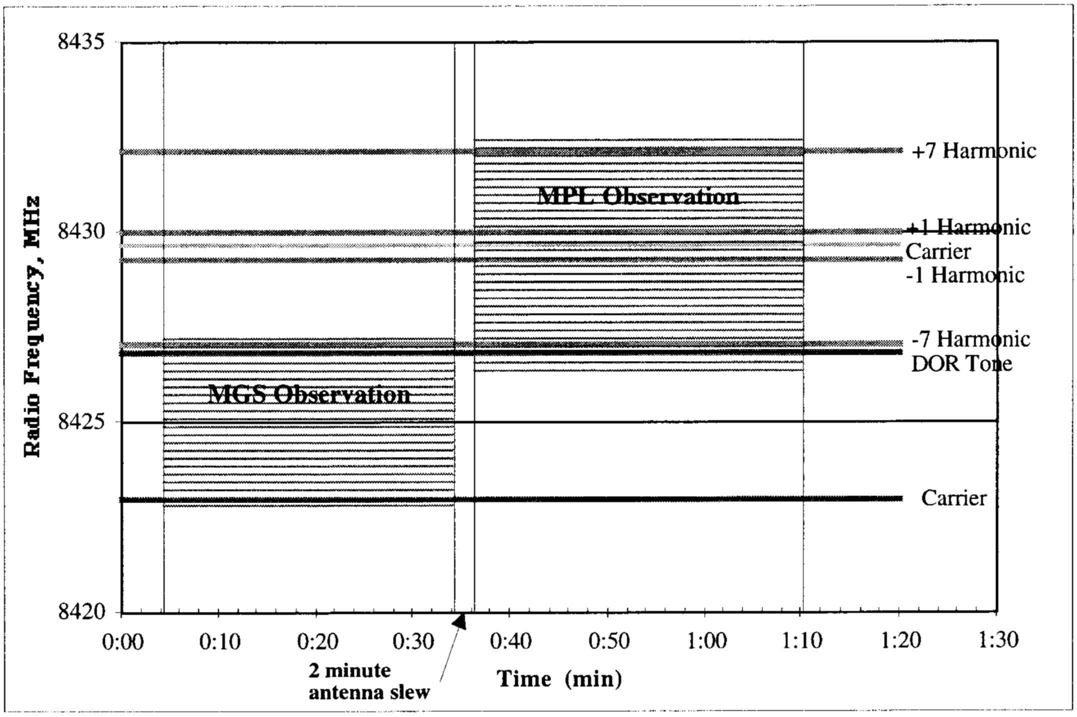


**Fig. 3:** Downlink Spectral Components and Observation Timing of MPL and MGS used for DDR[10]

Both spacecraft had to be configured to provide the appropriate downlink signal. For MGS, the DOR tones were turned on and the on-board ultra stable oscillator was selected as the reference for the one-way downlink. The signal strength was ample, so that telemetry and ranging modulations were left in their default states. The DOR tones were turned on just for the DDR measurement periods.

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[9] A one-way mode for MPL was also considered, but the DDR measurements were scheduled and sequenced before the first look at the MPL downlink spectrum.

[10] This plot depicts one scan for each spacecraft; in practice, 2-5 scans were made of each spacecraft for each DDR measurement.

For MPL, the 360 kHz telemetry sub-carrier was selected. The MPL signal is weak in comparison to the MGS signal, primarily due to the use of a medium gain antenna during cruise. To overcome this lower signal level, it was also necessary to increase the telemetry modulation index and turn off the ranging channel modulation. In addition, a low symbol rate was needed to reduce the squaring loss which occurs when telemetry harmonics are cross-correlated. This telemetry configuration was selected just for the DDR measurement periods.

### 4.3 - Validation Tests

The new system and procedures pulled together for this experiment needed to be validated before observables were delivered to the navigation team. In addition to internal consistency checks, these measurements had to be correct in an absolute sense if they were to be useful in the navigation process.

The first test done was to generate Doppler data with the FSR and compare it to Doppler generated by the Block V Receiver (which was used in generating the baseline Doppler data.) These two data sets agreed to within a few μHz. This verified the FSR open loop data files, as well as the timing of the FSR measurements (to an accuracy of 1 μsec, which was later corrected.)

Carrier phase data acquired using the FSR were also compared to carrier phase measurements acquired using another DSN tone tracker. The FSR data did agree with the tone tracker data. Finally, to prove that differential delay measurements would be correct, a zero baseline test was needed. By observing the MGS spacecraft in both the one-way and two-way downlink modes delay measurements of MGS could be made by the FSR that should produce the same result. The tests revealed a 0.6-nsec difference between one-way and two-way modes; dispersive instrumental effects were believed to be the cause.

### 4.4 - Observation Campaign

Four passes were scheduled between Nov. 3 and Nov. 19. The schedule had to account for MGS occultations and eclipses, and for MPL transitions from one-way to two-way. Two stations, a 34m antenna at Goldstone and a 70m antenna at Canberra, were used simultaneously to record the downlink signals from the two spacecraft, one at a time. Each spacecraft observation was about 30 minutes long, and it took about 2 minutes to slew antennas between spacecraft. The angular separation of the spacecraft was about 5 degrees.

### 4.5 - Measurement Results

The absolute accuracy, calculated as the RSS of the instrumental and random errors, came to 1.0 nsec, one sigma [JSB 99]. Other error sources, such as tropospheric delay and station location uncertainties, were small and did not significantly affect the result. A differential delay accuracy of 1.0 nsec over the Goldstone-Canberra baseline corresponded to and angular accuracy of 30 nrad.

## 5 - CONCLUSIONS

The NAG, by providing additional navigation expertise, was able to address the additional operational complexity of navigating the MPL/DS2 spacecraft, and make significant reductions in dynamic modeling uncertainty as well as trajectory uncertainty. At present, the NAG continues to meet regularly to review the status of other missions with navigation operations challenges; the lessons learned during MPL cruise are being passed on to other operations teams.

### 5.1 - Final MPL Navigation Results

As is mentioned in [PDB 00], in addition to the dynamics modeling difficulties, the nominal mission profile was still a navigation challenge: the tightest approach requirement was in the direction of the largest entry uncertainty. Nevertheless, the final trajectory reconstruction (based on tracking data collected between TCM-5 and the final turn to entry attitude) indicated the spacecraft were delivered within 0.15° of the target flight path angle, well within the 0.54° constraint.[11]

### 5.2 - MPL/DS2 Mission Results

MPL/DS2 approached Mars on 3 December 1999, on target and in apparent good health. At 12:02 p.m. PST, the spacecraft slewed to entry attitude. At this attitude, the antenna pointed off-Earth, and the signal was lost as expected. Lander touchdown was expected to occur at 20:14 p.m. GMT, with a 45-minute data transmission to Earth scheduled to begin 24 minutes later. It was also expected that the first data from the DS2 probes would be received on 4 December at 03:25 p.m. GMT, about 7 hours after MPL touchdown. However, no communications from MPL or the probes was received.

### 5.3 - Final Recommendations

In the subsequent findings of the JPL Special Review Board, many of their recommendations (in italics) were in alignment with those put forth by NAG team members:

> *Ensure that adequate attention is paid to spacecraft operability features (for example, coupled thrusters) if tight navigation control is required for the mission. Alternatively, if cost is the chief driver, accept larger accuracy errors by constraining landing site options.*
>
> Analysis tools should be developed with every new file format. Much of the work described here depended on *ad hoc* tools written on the fly to examine various aspects of small forces file information. A checklist of typical needs should be compiled to guide the development of these tools for any new format. The tools should be available for use by other projects, but need to be generalized and maintained in a multi-mission fashion to reach their widest utility.
>
> Also, spacecraft with unbalanced thrusters should return every single thruster firing at all times, instead of trying to compute and possibly accumulate $\Delta$Vs on-board, since the reliance on on-board models stifles the possibility of refining the modeling algorithms. None of this analysis would have been possible on MPL if the thruster impulses were accumulated over a fixed time or until a fixed threshold was reached, as is currently done on other spacecraft. If accurate spacecraft $\Delta$V calculations are ever demonstrated, only then should on-board compression techniques be considered to minimize telecommunications bandwidth.
>
> *Conduct in-flight validation of the assumed small-forces disturbance environment either with an early cruise calibration or via another on-board sensing technique (for example, appropriately scaled accelerometer, body-rate/impulse calibration).*

[11] The final trajectory reconstruction was based on tracking data collected between TCM-5 and the final turn to entry attitude.

Pre-flight ground calibration of thruster ΔVs to a level that permits the use of unbalanced thrusters on missions requiring high accuracy from only range and Doppler tracking has not been demonstrated. Consequently, in-flight calibration activities must be planned when unbalanced thrusters are to be used. A standard list of calibration activity considerations would be useful, so that issues do not get overlooked and are passed on from one project to the next.

Data types providing accurate measurements perpendicular to the geocentric direction (such as optical navigation, ΔDOR/DDR, and spacecraft-to-spacecraft Doppler) can be used to measure otherwise unobservable acceleration errors during a calibration phase, even if it occurs later than just after launch, and/or to render the navigation process relatively insensitive to a high level of acceleration error on the final approach to a target. Angular measurements of this type can also be used to refine the solar radiation pressure model, along with any other non-gravitational force apart from thruster usage, such that each model has a minimum of aliasing of errors from other models.

## 6 - ACKNOWLEDGEMENTS

The navigation tasks described here were part of a large collaborative effort across the project, technical divisions, and other directorates at the Jet Propulsion Laboratory. It is not simple to identify all of the contributors to the NAG-led tasks described here. Nevertheless, the authors would like to thank everyone who contributed to the rapidly performed analyses, tests, and measurements needed for this successful navigation effort.

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